CALIBRATION OF SENSORS FOR ANGULAR VIBRATION MEASUREMENTS

Lubomir Smutny [1], *Jiri Tuma* [2], *Radim Farana* [3]

[1] VSB –Technical University of Ostrava, OSTRAVA, Czech Republic, lubomir.smutny@vsb.cz
[2] VSB –Technical University of Ostrava, OSTRAVA, Czech Republic, jiri.tuma@vsb.cz
[3] VSB –Technical University of Ostrava, OSTRAVA, Czech Republic, radim.farana@vsb.cz

Abstract: The paper deals with the problem of the angular vibration sensor calibration. As a reference signal is produced by an incremental rotary encoder, which is a source of pulses. The pulse string determines the encoder rotation angle. The non-uniformity in the pulse distribution with respect to the rotation angle results in an error in determining the shaft rotation angle. The main topic of the paper is focused at the comparison of the encoder pair intended to employ for calibration of the Laser torsional vibration meter (BK 2523 type) based on the Doppler Effect. The method for evaluation of the rotation angle is based on the phase demodulation.

Keywords: angular vibration sensor, encoder, laser torsional vibration meter.

1. INTRODUCTION

The main sources of rotating machine vibrations are unbalance of rotors, misalignment of shafts and non-uniform driving torque. All these excitations result in dynamic force affecting bearing supports. Bearing vibration excites vibration of the machine housing, which increase the noise level. This paper is focused at the shaft angular vibration as a consequence of the non-uniformity of driving torque.

Rotational speed is measured in terms of the number of revolutions per minute (RPM) while the angular vibration is measured in terms of the angle, angular velocity or angular acceleration. The uniform rotational speed at the constant RPM corresponds to growing up the shaft angle proportionally to the elapsed time. The angle time history, having the form of the sum of a term that is depending linearly on time and a term that is randomly or regularly varying in time around zero, results from angular vibration during rotation. The angular velocity is obtained as the first derivative of the angle while the angular acceleration is evaluated as the second derivative of the angle.

There are many possible approaches to measuring angular vibration during rotation
- Tangentially mounted accelerometers
- Laser torsional vibration meter based on the Doppler effect
- Incremental rotary encoders (several hundreds of pulses per revolution).

In practice, measurements based on the use of encoders dominate. Instantaneous angular velocity is proportional to the reciprocal value of the time interval, which is elapsed between consecutive impulses. The measurement methods for the length of the time interval measurements are as follows:

- Sample number & Interpolation
- High frequency oscillator (100 MHz) & Impulse counter
- Phase demodulation.

The simplest method for evaluation of the instantaneous rotational speed is the reciprocal value of the time interval between two consecutive pulses. If the impulse signal is sampled then the time interval between the adjacent impulses is determined by interpolation of some values 50 times more accurately than indicated by the actual sampling interval. The accuracy is satisfying for the RPM measurement based on only one pulse per shaft rotation.

This method is not suitable if the large number of pulses per revolution is generated, which results in a few samples between impulses and the time interval length is impossible to estimate at satisfying accuracy. If the strings of encoder impulses as an analogue signal controls a gate for the high frequency clock signal (up to 10 GHz) that is an input of an impulse counter then this method works properly. This principle is implemented in the signal analyzers produced by Rotec. The primary output of these analyzers is angular velocity.

The approach of this paper is dealing with accuracy of the angular vibration measurements based on the impulse signal phase demodulation using the theory of complex analytic signals, which imaginary parts are the Hilbert transform of its real parts.

2. PRINCIPLE OF THE PHASE DEMODULATION

The angular vibration can be measured by using shaft encoders giving usually a train of pulses, rather then a sinusoid. As the impulse signal consists of several harmonics of the basic impulse frequency the first step in phase demodulation procedure is to separate the frequency band containing a carrier component and with sideband components by using a band-pass filter [3].
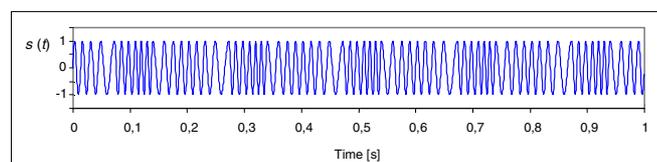

Fig. 1. Phase-modulated signal

An example of the phase-modulated signal is shown in Figure 1. The Fourier transform of real signals is composed from complex conjugate pairs of components with a positive and negative frequency (greater than the Nyquist frequency).

The Hilbert transform in the frequency domain can be expressed as a frequency transfer function shifting the phase of each mentioned component by $-\pi/2$ or $+\pi/2$, which means multiplying them by either -j or +j. The frequency range of the sampled real signals is limited to half the sampling frequency, $f_S/2$ (Nyquist frequency). Therefore, the argument of the transfer function is limited to the interval $(-\pi, +\pi)$

$$G_{HT}\left(\exp(j\omega)\right) = \begin{cases} -j, & +\pi > \omega \geq 0 \\ j, & -\pi < \omega < 0 \end{cases} \quad (3)$$

, which gives an impulse response

$$g_{HT}(n) = \frac{1}{2\pi}\int_{-\pi}^{+\pi} G_{HT}\left(\exp(j\omega)\right)\exp(j\omega n)d\omega = \begin{cases} 0, & n = 2k \\ 2/\pi n, & n = 2k+1 \end{cases}$$
$$(4)$$

The digital filter performing the Hilbert transform is called the Hilbert transformer. It is a high-pass or band-pass filter of the FIR (Finite Impulse Response) or IIR (Infinite Impulse Response) filter type. The phase modulated harmonic signal *s(t)* is put in the Hilbert transformer to obtain the Hilbert transform *y(t)* giving the imaginary part of an analytic signal (see Figure 2). The group delay of the Hilbert transformer using the FIR filter is equal to half the digital filter order; therefore the real part of the analytic signal *x(t)* is delayed by *n/2* samples.
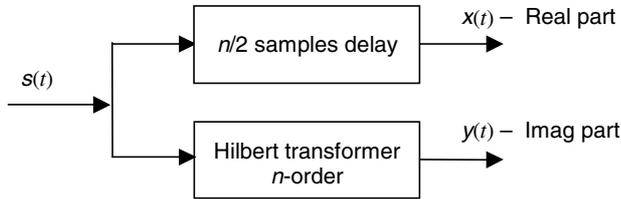

Fig. 2 HT using digital filters

The angle $\varphi_n = \mathrm{atan}\left(y_n/x_n\right)$ of the complex values $x_n + j\,y_n$ ranges from $-\pi$ to $+\pi$ and contains jumps at $-\pi$ at or $+\pi$ (see Figure 3). The true phase φ_n of the analytical signal as the time function must be unwrapped. The unwrapping algorithm is based on the fact that the absolute value of the phase difference $\Delta\varphi_n = \varphi_n - \varphi_{n-1}$ between two consecutive samples of the angle is less than π.

$$\Delta\varphi_n < -\pi \Rightarrow \varphi_n + 2\pi \to \varphi_n, \quad \Delta\varphi_n > +\pi \Rightarrow \varphi_n - 2\pi \to \varphi_n \quad (5)$$
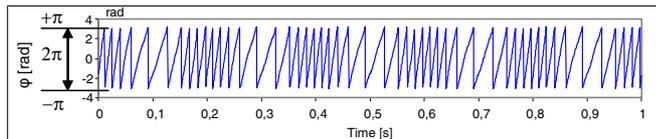

Fig. 3. Phase of analytical signal ranging from −π to +π

The phase on this diagram is not a linear function of time, but adding a harmonic signal to the linear function influences it. The unwrapped phase change per one complete rotation is equal to the 2π multiplied by the number K of the impulses per rotation. To evaluate uniformity of rotation the phase normalization has to be performed:

$$\varphi_n/K \to \varphi_n, \quad n = 0,1,...,N-1 \quad (3)$$

The phase normalization results in the diagram phase scale that corresponds to an angle of the complete revolution. The corresponding angle of rotation is a function composed from a linear term and phase modulation signal. The linear term corresponds to the steady-state rotational speed. After removing the linear term the phase modulation signal φ is obtained and it is seen on the right diagram in Figure 4.
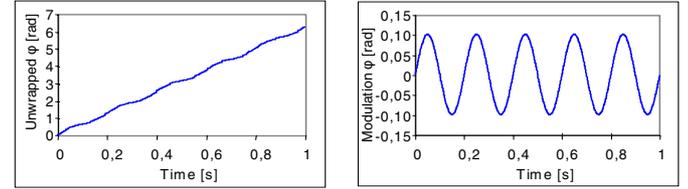

Fig. 4. Unwrapped and removed linear trend in phase of analytical signal

3. INCREMENTAL ROTARY ENCODER ACCURACY

Both the encoders under test shown in Figure 5 are of Heidenhain origin, the ERN 460-500 type producing 500 pulses per revolution..
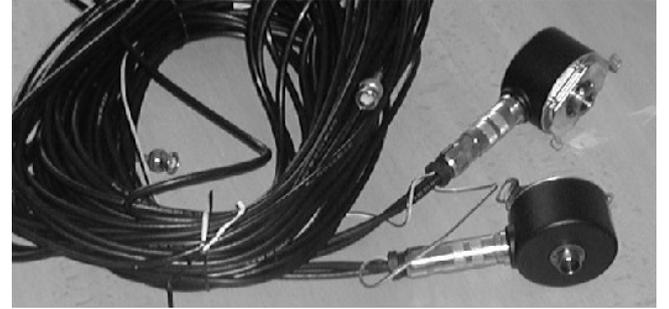

Fig. 5. Heidehain encoders of the ERN 460-500 type (500 pulses per revolution)

To evaluate errors in pulses distribution against the angle of rotation, both the encoders were mounted on a shaft what ensured the same rotational speed of them (see Figure 6).
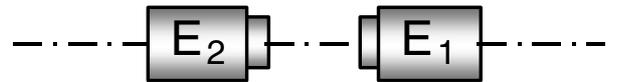

Fig. 6. Arrangement of encoders to be tested

Accuracy was assessed at the rotational speed of 634 and 1040 RPM. The pulse string generated by encoders was sampled at the frequency of 65536 Hz for 1040 RPM and at the frequency of 16384 Hz for 634 RPM.

As the running was not perfectly uniform from the point of the measurement method sensitivity, both the pulse signals were under influence of phase modulation. The encoder speed variation results in the phase modulation of the impulse signal base frequency. As noted above the phase-modulated signal contains sideband components around the carrying component. The frequency of the carrying component is equal to the 500th multiple (Order) of the encoder rotational frequency as it is shown in Figure 7. Using the analytical method described above, the phase

difference between modulation signals gives the error in pulse distribution.
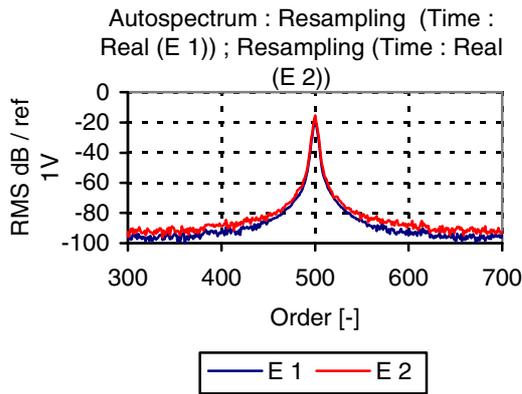

Fig. 7. Frequency spectrum of phase modulated signal generated by the E1 and E2 encoders

The time history of the mentioned error for the first 3 complete revolutions at 1040 RPM is shown in Figure 8. The time axis is in revolutions, which is in fact the dimensionless quantity related to the time interval elapsed during one complete encoder revolution.
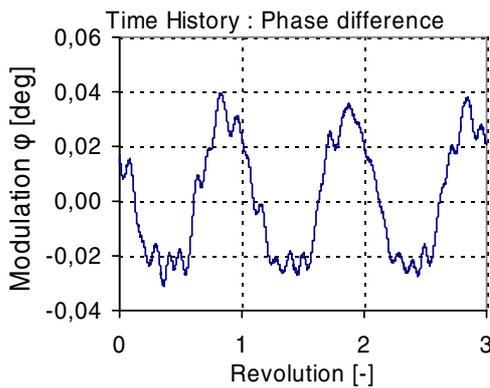

Fig. 8. Phase difference during 3 complete encoder revolutions

Synchronized averaging according to the rotational frequency is a signal processing tool, which results in the averaged time record of the phase difference, which is shown in Figure 9.
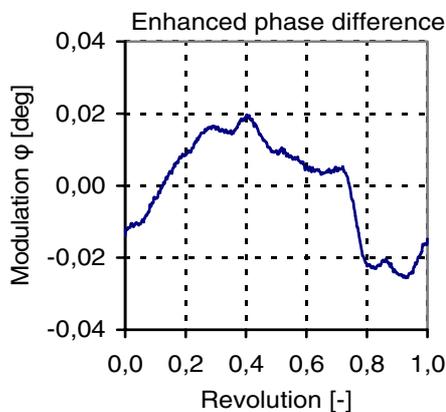

Fig. 9. Phase difference during a complete encoder revolution for 1040 RPM

The frequency spectrum of the resulting error is shown in Figure 10. The frequency axis is in orders. The quantity "Order" determines a part of a circle related to the error level. The error of determination the angle rotation over the arbitrary number of adjacent pulses is given by the sum of individual errors corresponding to the rotation by a pulse. The summation process results in the dependence of the error on the order with the roll-off corresponding to the error decade per the order decade.
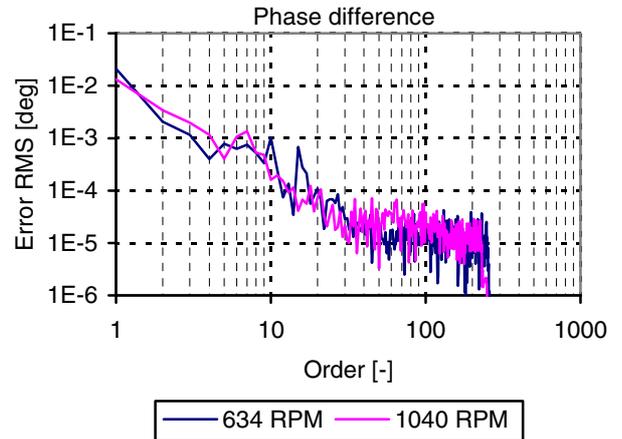

Fig. 10. Spectrum of the phase difference for 634 and 1040 RPM

4. COMPARISON OF THE LASER AND ENCODER MEASUREMENTS

An experimental setup is shown in figure 11. The experiment was aimed at the problem of drilling tool rotation uniformity measurements. Additionally to the encoder the torsional vibration meter type 2523 of the Brüel & Kjær origin was employed. This laser equipment consists of a meter and a dual beam laser transducer. The type 2523 determines the instantaneous changes in angular velocity, and, by integration, in angular displacement, of a rotating component from the frequency difference of the retro reflected, Doppler-shifted beams. The measurement accuracy is equal to 1% of full scale (2% for speeds less than 100 RPM). For the measurement range of 1000 deg/s the laser sensor error is less than 10 degrees per second. The laser sensor measurements were compared with the mentioned encoder measurements. The first derivative of the encoder modulation signal with respect to time gives the angular velocity of rotation in degrees per second.

Fig. 11 Experimental stand with laser instrumentation

To evaluate this derivative the FIR filter was employed. Using this filter the high frequency components, exceeding 1 kHz, were filtered out.

The time history of both the sensor outputs is shown in Figure 12. The laser output signal is delayed by 3,296 ms to the encoder signal. The frequency spectra of both the signals are shown in Figure 13. Tests show that both this measurements are almost the same.

3. CONCLUSION

Contribution shows the problem of the angular vibration sensor calibration. As a reference signal was produced by an incremental rotary encoder, which was a source of pulses and the pulse string determines the encoder rotation angle. The non-uniformity in the pulse distribution with respect to the rotation angle results in an error in determining the shaft rotation angle.

The frequency of pulses, which are generated by the encoder attached to a shaft, is proportional to the shaft rotational speed. The main topic of the paper was focused at the comparison of the encoder pair intended to employ for calibration of the Laser torsional vibration meter (BK 2523 type) based on the Doppler Effect. The method for evaluation of the rotation angle is based on the phase demodulation. Tests show that the errors in pulse distribution as a function of the angular displacement are not exceeding an angular second for high frequency components. Measurements, which were done by using the encoder and laser, result in the same outputs.

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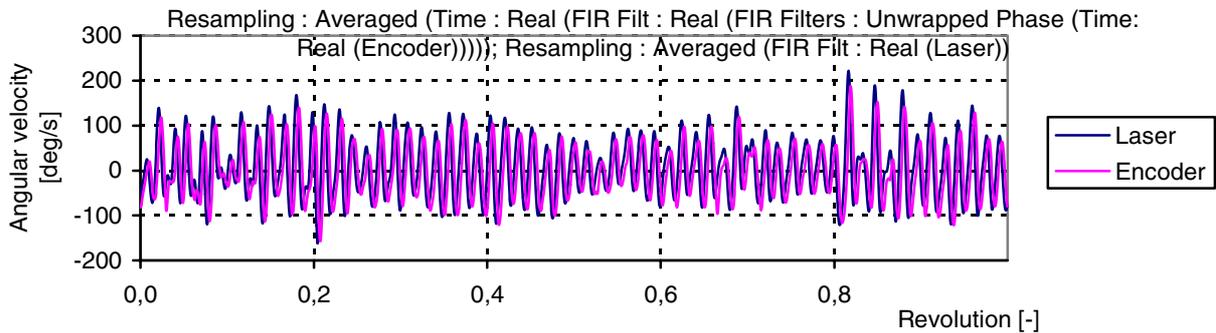
Fig. 12. Laser vibration signal vs. encoder after phase demodulation and differentiation
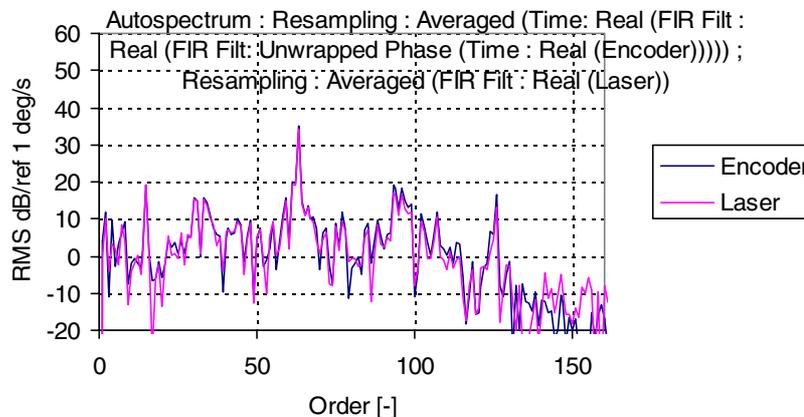

Fig. 13. Frequency spectrum of angular vibration in dB scale (ref. 1 deg/s)